Auto-detection and censusing of blue whale vocalizations along the central California Coast using a bottom-lying hydrophone array

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Abstract

To investigate the feasibility of automating the detection and censusing of blue whale vocalizations over a large coastal region using the Naval Postgraduate School (NPS) Ocean Acoustic Observatory (OAO), a four-day experiment was conducted along Central California in the summer of 1997. During the experiment, array data was archived continuously at the NPS OAO, a former US SOSUS array. In addition to shore-based acoustic monitoring, an aircraft was assigned to locate blue whales in the Monterey Bay National Marine Sanctuary, and a research vessel, manned with observers and instrumented with a towed hydrophone array, was used to confirm locations of the blue whales and classify the vocalized near-field signals. The shipboard measurements were required to provide a means to separate the source signal characteristics from their multipath signatures for the design of long-range auto-detection and censusing algorithms. The towed array data was deverberated, source level and characteristics were estimated, and call-to-call variability was studied. Determination of robust signal parameters is important to the design of auto-detection filters as well as optimal matched-signal (field) algorithms for long-range localization and tracking using the NPS OAO array. Results toward showing the feasibility of these concepts are discussed. [Research supported by SERDP/ONR]

Background

Counting and tracking whale populations has relied on aircraft and ship-based visual techniques. Drawbacks of these visual techniques include high cost, limited coverage and poor accuracy. A factor that contributes to the latter is that the long-diving whales may not clearly present themselves during a survey and therefore are difficult to track by human observers. A better understanding of the whale population and their migration routes clearly requires improved censusing methods.

Acoustical monitoring of vocalizing blue whales using shore-based hydrophone arrays could offer unique advantages over the visual techniques. Blue whales have been observed to frequent the Monterey Bay National Marine Sanctuary (MBNMS). They produce primarily low-frequency sounds which are perhaps some of the best studied whale sounds (Cummings and Thompson, 1971, Moore, 1999, among many others). The vocalizations of the Northeastern Pacific blue whales generally consist of a sequence alternating "A" and "B" calls. The A call can be characterized as a train of amplitude-modulated short pulses with a fundamental carrier frequency at about 18 Hz and a strong fifth harmonic at 90 Hz. The B call corresponds to a long frequency-modulated moan with a fundamental at 17 Hz and a strong third 51-Hz harmonic. The

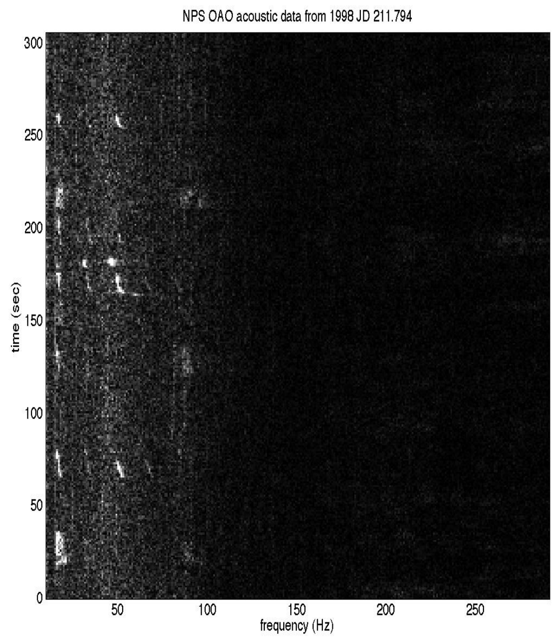

Fig. 1. The spectrogram of a segment of the continuous time-series recorded by one of the hydrophones of the shore-based NPS OAO array, showing alternating A and B calls of a blue whale.

blue whale calls are frequently detected by the Naval Postgraduate School (NPS) Ocean Acoustic Observatory (OAO) hydrophone array during summer. The spectrogram of a short segment of the time series measured by one of the hydrophones of the array is shown in Figure 1. The calls of a transiting blue whale can be easily observed.

The NPS OAO hydrophone array was a SOund SUrveillance System (SOSUS) array disbanded by the US Navy after the Cold War. NPS officially took possession of the building complex where the array terminates in 1996. Partnering with several external oceanographic academic institutions, the functionality of the listening array has been largely restored for the purpose of scientific research and graduate education. Currently, data from 24 hydrophones are being continuously acquired and archived at a sampling rate of 2 kHz with a real-time data acquisition system. The array is located in the southern portion of the MBNMS on the seafloor.

Scientific Goal and the Feasibility Experiment

Our scientific goal is to demonstrate that vocalizing blue whales in the MBNMS can be censused and tracked continuously and efficiently on a long-term, real-time basis using shore-based horizontal hydrophone arrays. The NPS OAO array system was designed to optimally focus on low-frequency signals which, with a moderate source level, can propagate efficiently and be detected by directional, noise-reduced acoustic beams over distances exceeding several hundreds of kilometers, i.e., the dimensions of the MBNMS.

Research into the feasibility of automating the detection, tracking and censusing of vocalizing blue whales in the MBNMS using the NPS OAO hydrophone array began two years ago at NPS under SERDP/ONR sponsorship. A four-day feasibility experiment was carried out in the summer of 1997 (Chiu et al., 1997) to collect the needed data for this research. During the experiment, array data was archived continuously at the NPS OAO. In addition to shore-based acoustic monitoring, an aircraft was assigned to locate blue whales in the Monterey Bay National Marine Sanctuary, and a research vessel, manned with observers and instrumented with a towed hydrophone array, was used to confirm locations of the blue whales and classify the vocalized near-field signals. The shipboard measurements were required to provide a means to separate the source signal characteristics from their multipath signatures for the design of long-range auto-detection and censusing algorithms. Extraction of robust source signal parameters from the "deverberated" signals, i.e., actual source signals, is crucial to the design of auto-detection filters as well as algorithms for long-range localization and tracking using the NPS OAO array.

Technique and Results

The near-field towed-array data has been "deverberated" to allow for a quantitative examination of the source level, source signal characteristics and call-to-call variability. The deverberation technique used is described next:

The frequency spectra R_p of the received signals are related to the spectrum S of the source signal weighted by the source-to-receiver transfer function H, and contaminated by additive noise N:

$$R_p(f) = S(f;\vec{x}_w)\ H(f;\vec{x}_w,\vec{x}_p) + N(f). \qquad (1)$$

Because we are dealing with measurements near the whale site, it is adequate to model model H with five multipaths:

$$H(f;\vec{x}_w,\vec{x}_p) = \sum_{j=1}^{5} \frac{w_j}{D_j} e^{-i2\pi f \tau_j}, \qquad (2)$$

where D_j is the path length of the j[th] path, τ_j is the corresponding travel time, and W_j is the corresponding weighting factor. The five paths include a direct path, one with one surface bounce, one with one bottom bounce, one with two surface bounce and a bottom bounce, and one with one surface bounce and a bottom bounce. W_j depends on the number of surface/bottom reflections, the surface/bottom reflection coefficients, the incident angle, and for the direct path it is unity. It is clear in (1) that the reconstruction of S requires that the location $\vec{x}_w$ of the whale to be known first.

To estimate the whale location, we first plane-wave beamformed to determine the bearing. We then adopted the matched-signal processing method introduced by Parvulescu (1961 and 1995) to estimate range and depth. With an array of multiple elements at known relative positions $\vec{x}_p$, the matched-signal method can be generalized to become a space-time processor. An ambiguity surface, a function of range and depth, can be calculated by correlating the received signals with the transfer functions and then storing the maximum correlation value:

$$a(x,z) = \max_{\tau} \left\{ \int_{-\infty}^{+\infty} \underline{R}^H(f)\, \underline{H}(f;x,z)\, e^{i\,2\pi\, f\tau} \right\} \quad (3)$$

where $\underline{R}$ and $\underline{H}$ are now vector functions containing multiple received signals and transfer functions associated with each of the hydrophone elements. The best location estimate $(\hat{x}, \hat{z})$ is where the ambiguity surface attains its maximum. With the location estimate, the source signal can be reconstructed using least-squares estimation:

$$\hat{S}(f) = \left[\underline{H}(f,\hat{x},\hat{z})^H H(f,\hat{x},\hat{z})\right]^{-1} H(f,\hat{x},\hat{z})^H R(f). \quad (4)$$

An example of our deverberation results is displayed in Figure 2, with the bottom panel showing the recordings of an A call obtained by the different hydrophones of the towed array. Based on these measurements, matched signal processing was first employed to calculate an ambiguity surface (top panel) from which the whale position was estimated. With the whale position known, least-squares estimation was then used to unscramble the multipath signatures for the true source signal (middle panel).

The signal characteristics and call-to-call correlation estimated from numerous deverberated A and B calls are summarized in Table 1. These calls were produced by two different blue whales in transit. Important to note is that the B call waveforms are highly correlated whereas the A call waveforms are not. Strong similarity between the structure-rich A calls, however, are found in the magnitude of the waveforms. Clearly, auto-detection matched filters can be built based on signal models resembling the mean of the normalized B call waveforms and the mean of the magnitude of the normalized A call waveforms, respectively.

	Source Level (re 1 μPa)	Duration	Call-to-Call Correlation: Waveform	Call-to-Call Correlation: Magnitude of Waveform
A Call, 5th Harmonic	158 ±• 5 dB	~ 15 s	0.3	**0.9**
B Call, 3rd Harmonic	157 ± 6 dB	~ 10 s	**0.7**	0.9

Table 1: Summary of signal characteristics and call-to-call correlation estimates.

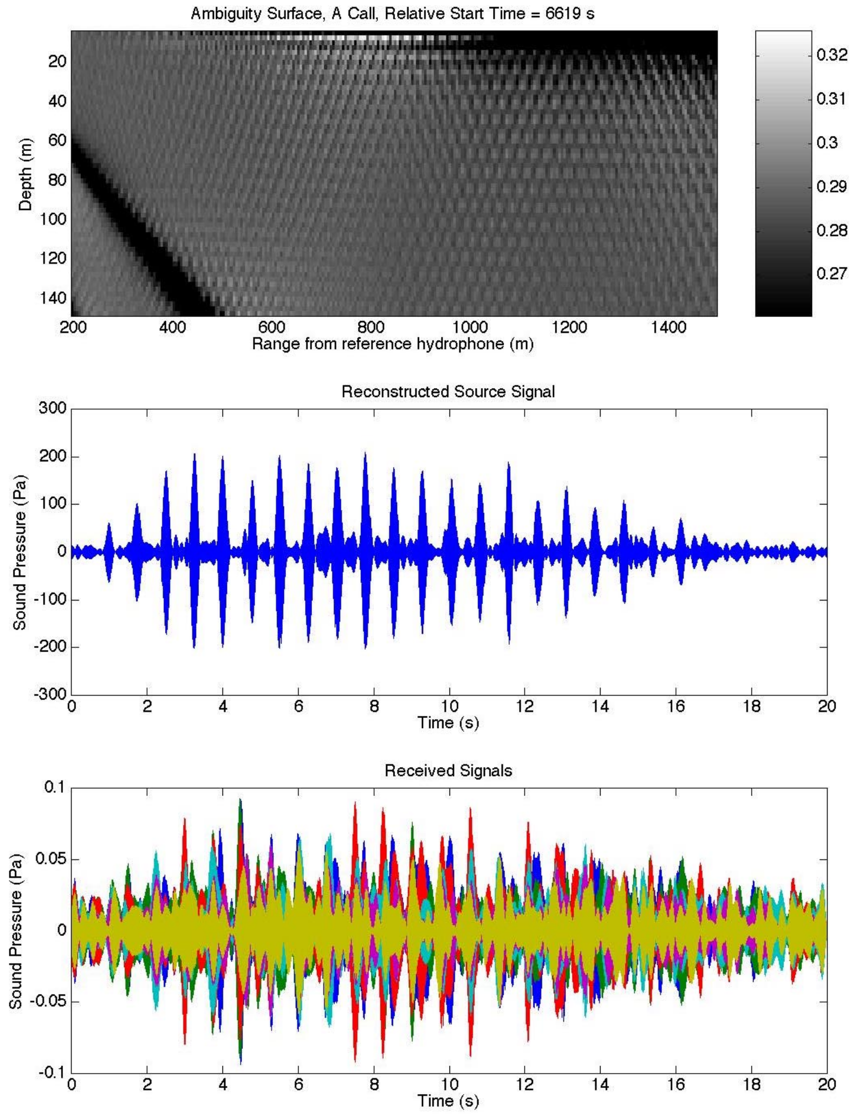

Fig. 2. The deverberation of a blue whale A call. An ambiguity surface (top) was calculated from applying a matched signal method to the signals (bottom) received by the different hydrophones of an array. The highest correlation grid point gave the best estimate of the whale location. With the location known, the received multipath signals were then deverberated to reconstruct the source signal produced by the whale (Middle).

Concluding Remarks

Two auto-detection matched filters for the blue whale A and B calls are currently being tested and calibrated with the far-field NPS OAO array data. After thoroughly tested and validated, we plan to implement these auto-detection algorithms for real-time applications.

On long-range localization and tracking using the NPS OAO array, Hager (1997) shows, in a computer simulation experiment, that using matched signal methods, vocalizing blue whales in the MBNMS can, in principle, be located unambiguously using the NPS OAO array alone. However, the size and resolution of the search grid for the entire MBNMS would render these type of methods computationally formidable for real-time purposes. We are currently proposing another real-time bottom-lying array to be instrumented near the northern boundary of the MBNMS. With two real-time arrays located at two complimentary geographic locations, the horizontal location of a vocalizing blue whale can be rapidly estimated based on simplistic triangulation schemes applying to beamformed bearing information and arrival times of the signal. Matched signal methods can then be used to search over a single dimension only to obtain the depth of the vocalizing whale.

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